PROGRESS TOWARDS USING A CALCIUM ION TRAP TO PERFORM QUANTUM LOGIC OPERATIONS

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We briefly review the development and theory of an experiment to investigate quantum computation with trapped calcium ions. The ion trap, laser and ion requirements are determined, and the parameters required for simple quantum logic operations are described. *

INTRODUCTION

In the last 15 years various authors have considered the generalization of information theory concepts to allow the representation of information by quantum systems. The introduction into computation of *quantum mechanical* concepts, in particular the superposition principle, opened up the possibility of new capabilities, such as quantum cryptography [1], that have no classical counterparts. One of the most interesting of these new ideas is quantum computation, first proposed by Benioff [2]. Feynman [3] suggested that quantum computation might be more powerful than classical computation, a notion which gained further credence through the work of Deutsch [4]. However, until quite recently quantum computation was an essentially academic endeavor because there were no quantum algorithms that exploited this power to solve useful computational problems, and because no realistic technology capable of performing quantum computations had been envisioned. This changed in 1994 when Shor discovered quantum algorithms for efficient solution of integer factorization and the discrete logarithm problem [5, 6], two problems that are at the heart of the security of much of modern public key cryptography [7]. Later that same year Cirac and Zoller proposed that quantum computational hardware could be realized using known techniques in the laser manipulation of trapped ions [8]. Since then interest in quantum computation has grown dramatically, and remarkable progress has been made: a single quantum logic gate has been demonstrated with trapped ions [9]; quantum error correction schemes have been invented [10, 11]; several alternative technological proposals have been made [12, 13, 14, 15, 16, 17] and quantum algorithms for solving new problems have been discovered [18, 19, 20, 21]. In this paper we will review our development of an experiment to investigate the potential of quantum computation using trapped calcium ions [22].

The three essential requirements for quantum computational hardware are: (1) the ability to isolate a set of two-level quantum systems from the environment for long enough to maintain coherence throughout the computation, while at the same time being able to interact with the systems strongly enough to manipulate them into an arbitrary quantum state; (2) a mechanism for performing quantum logic operations: in other words a “quantum bus channel” connecting the various two-level systems in a quantum mechanical manner; and (3) a method for reading out the quantum state of the system at the end of the calculation. All three of these requirements are in principle met by the cold trapped ion quantum computer. In this scheme each qubit consists of two internal levels of an ion trapped in a linear configuration. In order to perform the required logic gates, a third atomic state known as the

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auxiliary level is required. The quantum bus channel is realized using the phonon modes of the ions' collective oscillations. These quantum systems may be manipulated using precisely controlled laser pulses.

CHOICE OF ION

Various ions used in atomic frequency standards work satisfy the requirements to be a qubit. Of these ions, Ca^+ offers the advantages of transitions that can be accessed with titanium-sapphire or diode lasers and a reasonably long-lived metastable state to allow computations to take place. The relevant energy levels of the $A = 40$ isotope are shown in Fig.1.

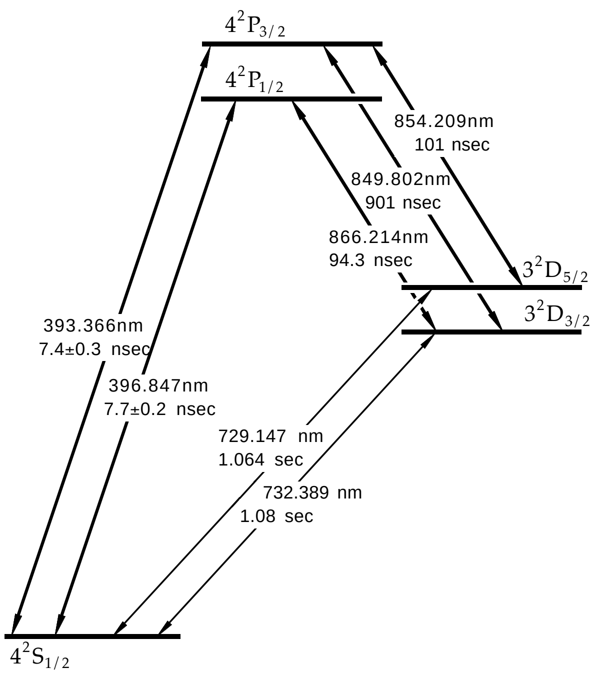

Figure 1. The lowest energy levels of $^{40}Ca^+$ ions, with transition wavelengths and lifetimes listed.

The dipole-allowed transition from the $4\,^2S_{1/2}$ ground state to the $4\,^2P_{1/2}$ level with a wavelength of 397 nm can be used for Doppler cooling and quantum jump readout; The 732 nm electric quadrupole transition from the $4\,^2S_{1/2}$ ground state to the $3\,^2D_{3/2}$ metastable level (lifetime $\approx 1.08 sec.$) is suitable for sideband cooling. In the single laser computation scheme, the qubits and auxiliary level can be chosen as the electronic states

$$\begin{aligned} |0\rangle &= |4\,^2S_{1/2},\, M_j = 1/2\rangle, \\ |1\rangle &= |3\,^2D_{5/2},\, M_j = 3/2\rangle, \\ |aux\rangle &= |3\,^2D_{5/2},\, M_j = -1/2\rangle. \end{aligned}$$

This ion can also be used for Raman type qubits, with the two Zeeman sublevels of the $4\,^2S_{1/2}$ ground state forming the two qubit states $|0\rangle$ and $|1\rangle$, with one of the sublevels of the $4\,^2P_{1/2}$ level being the upper level $|2\rangle$. A magnetic field of 200 Gauss should be sufficient to split these two levels so that they can be resolved by the lasers. The pump and Stokes beams would be formed by splitting a 397nm laser into two, and shifting the frequency of one with respect to the other by means of an acousto-optic or electro-optic modulator. This arrangement has an advantage in that any fluctuations in the phase of the original 397nm laser will be passed on to both the pump and Stokes beams, and will therefore be canceled out, because the dynamics is only sensitive to the difference between the pump and Stokes phases.

EXPERIMENTAL APPARATUS

In our experiment ions are confined in a linear RF quadrupole trap [22]. Radial confinement is achieved by a quadrupole RF field provided by four 1 mm diameter rods in a rectangular arrangement. Axial confinement is provided by DC voltages applied to conical endcaps at either end of the RF structure; the endcap separation is 10 mm. The design of the trap used in these experiments is shown in diagrammatically in Fig.2.

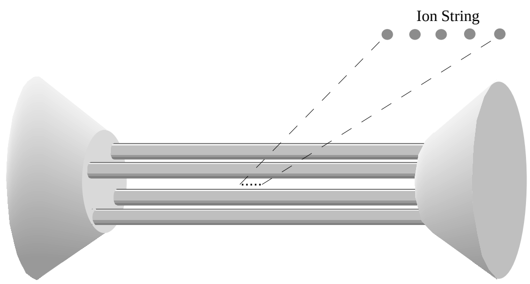

Figure 2. Side view diagram of the linear RF trap used to confine Ca^{+} ions in these experiments. The endcap separation is 10 mm and the gap between the RF rods is 1.7 mm.

The first stage of cooling is to cool a small number of ions to their Doppler limit in the ion trap. This requires a beam at 397 nm, the $4\,^2S_{1/2} - 4\,^2P_{1/2}$ resonant transition. Tuning the laser to the red of the transition causes the ions to be Doppler cooled. Having carefully selected the trap parameters, many cycles of absorption and re-emission will bring the system to the Lamb-Dicke regime, leaving the ions in a string-of-pearls geometry. We have recently found ion crystals of up to thirteen Ca^{+} ions. Fig.3. shows a typical string of ions. The fluorescence signal from the ions is detected perpendicular to the trap axis by an image intensified CCD camera and independently by a photomultiplier mounted on the opposite side of the trap. The photomultiplier is used to observe the 397 nm fluorescence spectra both for detuning of the 397 nm and the 866 nm lasers from resonance to establish the exact line positions.

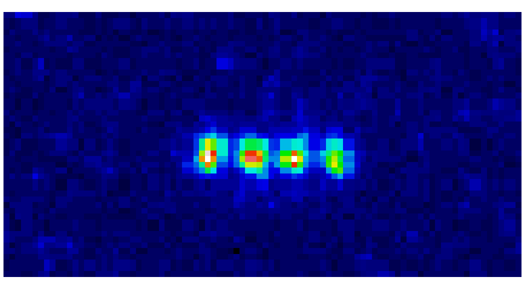

Figure 3. Image of a string of four trapped calcium ions. The total length is roughly 80 μm.

In order to Doppler cool the ions, we use a Titanium:Sapphire (Ti:Sapphire) laser (Coherent CR 899-21) with an internal frequency doubling crystal to produce the 397 nm light. We are also developing a diode laser with a frequency doubling cavity to produce 397 nm light, which will be a smaller, less expensive alternative to the Ti:Sapphire laser. During the Doppler cooling, the ions may decay from the $4\,^2P_{1/2}$ state to the $3\,^2D_{3/2}$ state, whose lifetime is $\sim$ 1sec. To empty this metastable state, we use a diode laser at 866 nm.

Once the string of ions is Doppler cooled to the Lamb-Dicke regime, the second stage of optical cooling, sideband cooling, will be used to reduce the collective motion of the string of ions to its lowest vibrational level [25]. In this regime, a narrow optical transition, such as the 732 nm $4\,^2S_{1/2} - 3\,^2D_{3/2}$ dipole forbidden transition, develops sidebands above and below the central frequency by the vibrational frequencies of the ions. The sidebands closest to the unperturbed frequency correspond to the CM vibrational motion. If ω_0 is the optical transition frequency and ω_x the frequency of the CM vibrational motion, the phonon number is increased by one, unchanged, or decreased by one if an ion absorbs a photon of frequency $\omega_0+\omega_x$, ω_0 or $\omega_0-\omega_x$, respectively. Thus, sideband cooling is accomplished by optically cooling the string of ions with a laser tuned to $\omega_0-\omega_x$.

The need to resolve the sidebands of the transition implies a much more stringent requirement for the laser linewidth; it must be well below the CM mode vibrational frequency of $\sim(2\pi)\times 200$ kHz. The laser power must also be greater in order to pump the forbidden transition. We plan to use a Ti:Sapphire laser locked to a reference cavity to meet the required linewidth and power. The transitions required for realization of quantum logic gates and for readout can be performed with the same lasers used in the Doppler and sideband cooling procedures.

QUBIT ADDRESSING OPTICS

In order for the Ca^+ ion qubits to be useful for actual calculations, it will be necessary to address the ions in a very controlled fashion. Our optical system for qubit addressing is shown schematically in Fig.4.

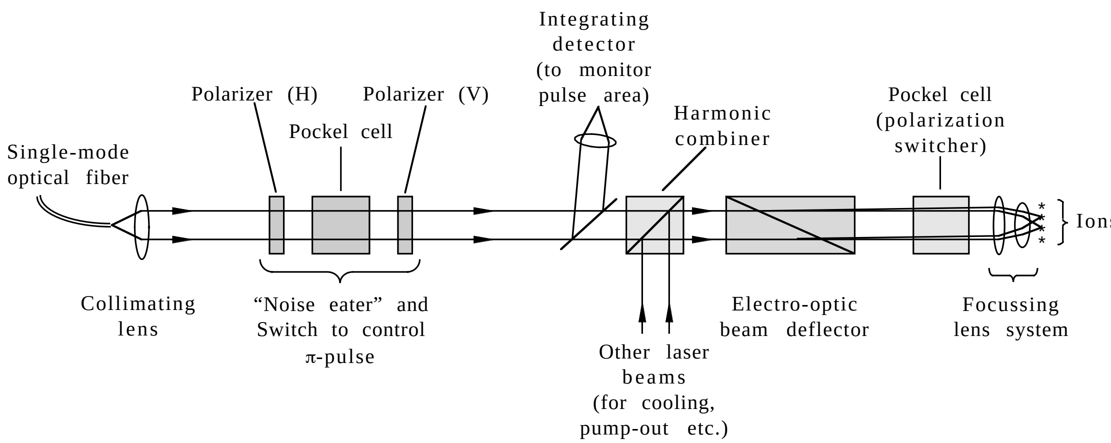

Figure 4. Illustration of the laser beam control optics system.

There are two aspects to be considered in the design of such a system: the precise interactions with a single ion; and an arrangement for switching between different ions in the string. In addition to the obvious constraints on laser frequency and polarization, the primary consideration for making exact π- or 2π-pulses is control of the area (over time) of the driving light field pulse. The first step toward this is to stabilize the intensity of the laser, as can be done to better than 0.1%, using a standard "noise-eater". Switching the light beam on and off can be performed with a similar (or even the same) device. Because such switches can possess rise/fall times on the scale of nanoseconds, it should be possible to readily control the area under the pulse to within $\sim 0.1\%$, simply by accurately determining the width of the pulse.

The controls for switching between ions must be fast, reproducible, display very precise aiming and low "crosstalk" (i.e. overlap of the focal spot onto more than one ion), and be as simple as possible. In particular, it is desirable to be able to switch between different ions in the string in a time short compared to the time required to complete a given π-pulse on one ion. This tends to discount any sort of mechanical scanning system. As a tentative solution, we propose to use an electro-optic beam deflector, basically a prism whose index of refraction, and consequently whose deflection angle, is varied slightly by applying a high voltage across the material; typical switching times for these devices is 10 nanoseconds, adequate for our purposes. We have also constructed a prototype system for testing the focussing lens system. With this test system, we can achieve a crosstalk of less than 0.2 percent for an ion spacing of 20 μm.

SUMMARY

In this paper we have described in some detail the experiment we are currently developing to investigate the feasibility of cold trapped ion quantum computation. We should emphasize that our intentions are at the moment exploratory: we have chosen an ion on the basis of current laser technology, rather than on the basis of which ion which will give the best performance for the quantum computer. Other species of ion may well give better performance: In particular Beryllium ions do have the potential for a significantly lower error rate due to spontaneous emission, although it is also true that lighter ions may be more susceptible to heating. Other variations, such as the use of Raman transitions in place of single laser transitions, or the use of standing wave lasers need to be investigated. Our choice of Calcium will allow us to explore these issues. Furthermore, calculations suggest that it should be possible to trap 20 or more Calcium ions in a linear configuration and manipulate their quantum states by lasers on short enough time scales that many quantum logic operations may be performed before coherence is lost. Only by experiment can the theoretical estimates of performance be confirmed [26, 27]. Until all of the sources of experimental error in real devices are thoroughly investigated, it will be impossible to determine what ion and addressing scheme enables one to build the best quantum computer or, indeed, whether it is possible to build a useful quantum computer with cold trap ions at all.

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